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BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 185

EXPERIMENTS ON COPPER CRUSHER CYLINDERS

BY

ALEXANDER I. KRYNITSKY, Associate Physicist
Bureau of Standards

FEBRUARY 1, 1921

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By Alexander I. Krynitsky

ABSTRACT

The experiments consisted of compression tests on a standard Riehlé testing machine. The results of these compressions carried out on annealed copper cylinders, one set having a mean length of 0.4000 inch and the others 0.5000 inch, with a mean diameter of 0.2260 inch in the former and 0.2500 and 0.2250 inch in the latter ones, suggest that the length of the cylinders decreased considerably under repeated application of the same and, within certain limits, of smaller loads.

In the case where the load is applied in such a manner as to produce the maximum stress for only an instant, the duration of an application of load has but little effect on the decrease in length of the cylinders, but the application of the same load by holding the beam balanced through an additional application of this load causes about twice the decrease in length as compared with that obtained by a single application of load. When two successive loads of considerable amount differing by increments of about 2000 pounds per square inch are applied, the second being greater than the first, the change in length due to the last load is greater than that obtained where the pressure is applied on previously uncompressed cylinders, and this difference decreases as the difference between the two loads successively applied increases, so that when the difference between the loads reaches a certain value the change of length due to the last load applied is practically independent of the previous load.

It appears probable that aging at temperatures within the range 0–100° C softens the compressed copper somewhat.

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I. INTRODUCTION

1. TWO METHODS FOR MEASUREMENT OF PRESSURE OF GASES IN TESTING OF POWDER AND AMMUNITION

Among many methods and apparatus [1] proposed for the measurement of pressure developed by the products of decomposition of powder in the testing of powder and ammunition there are two methods which up to the present time are commonly employed in practice; that is (1) the so-called dynamic method and (2) the method of measuring pressure by means of metallic cylinders, usually copper or lead cylinders, known as crusher cylinders.

The dynamic method consists of determining the velocities of the gun in recoil or of the shot at different points of the bore. The difference of the velocities divided by the corresponding differences of the time equal the acceleration. The pressure required to produce the observed acceleration in a body whose mass is that of the gun or of the projectile is obtained by multiplying the acceleration by the mass.

The crusher-gage method was proposed in 1868 by Noble, and up to the present time is regarded as the most convenient known method for obtaining an idea of the relative values of pressures in guns.

There is a metal cylinder set on an anvil. On firing, the pressure of the gases shortens the cylinder longitudinally. The amount of this compression, with a previously prepared table, so-called tarage table, serves to determine the maximum pressure of the products of decomposition. For the testing of small arms a special barrel is used. For example, in Figs. 1 and 2, a pressure-gage outfit

[1] It may be mentioned here that two types of registering apparatus proposed very recently appear very promising, and they possibly will find common use in the near future. One of these was proposed by Prof. A. G. Webster, of Clark University, and the other is designed to coordinate time and pressure within a large cannon, upon which Dr. H. L. Curtis and associates, of the electrical division of the Bureau of Standards, are working.

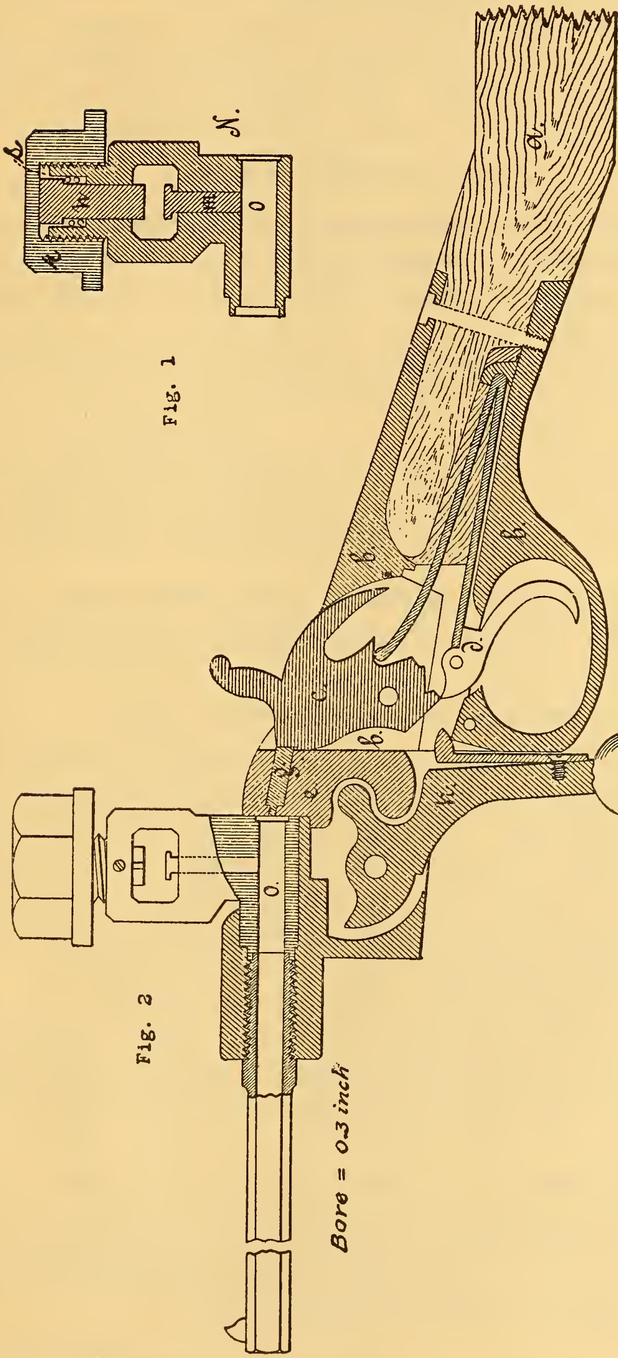

Fig. 1.—*Cross section of the pressure-gage attachment of Fig. 2*
Fig. 2.—*A pressure-gage outfit for Russian 0.3-inch revolver*

for Russian 0.3-inch revolver is shown: O = a special barrel; h = an unmovable piston fixed rigidly in its position by means of nut r and spring s; m = a movable piston. Between pistons h and m crusher cylinders are placed. By turning the nut r the crusher cylinder may be tightened between these two pistons.

2. COPPER CRUSHER CYLINDERS

In the present paper only copper crusher cylinders will be considered. Dimensions of copper cylinders vary in different countries and for pressure testing of different grades of ammunition and powder.

For example, some dimensions of copper crushers are as follows:

Dimensions	A	B	C	D
	mm	mm	Inch	Inch
Diameter	3	8	0. 2260	0. 2520
Height	4. 9	13	. 4000	. 5000

The copper must be exceptionally pure, and the whole process of manufacture of copper crushers should be standardized with extreme care.

3. PREPARING DATA FOR TARAGE TABLE

In preparing these data the copper cylinders are slowly compressed by applying the loads and measuring the amount of compression at each load. The load for each compression remains active for about 15 seconds. Ch. B. Wheeler,[2] from his experiments, found it might safely be assumed that at the end of 15 seconds the copper is practically in equilibrium with its load and that any further application of load produces no effect.

Influence of the friction of the testing machine is of great importance in the construction of tarage tables. As early as 1891 this was demonstrated by Vieille, who showed that neglect of this factor was responsible for the erroneous French crusher tables.

This point, states F. W. Jones,[3] must be insisted upon because experiments in some quarters assume friction is of no account, a conclusion to which they are driven because no provision has been made in the design of their testing machine for applying the load with friction acting alternately back and forth.

[2] Report of Experiments with an 8-inch B. L. Rifle Mounted on a Free Recoil Carriage, by Lieut. Ch. B. Wheeler, Ordnance Construction, Notes 69–85, pp. 46–56; Jan., 1896.

[3] A Standard Pressure Table for Copper Crushers, by F. W. Jones, Arms and Explosives, June 1, 1918.

4. COMPARISON OF PRESSURES INDICATED BY DYNAMIC AND CRUSHER-GAGE METHODS

The dynamic method shows a pressure which is less than the true pressure expected in the gun, as it takes no account of the pressure required to overcome the friction of the projectile in the bore and to rotate the projectile.

Comparing now the dynamic method and the crusher-gage method, we find that the latter gives pressures which are less than those shown by the dynamic method.

According to B. W. Dunn,[4] under ordinary service conditions (since the time required by powder pressure to reach a maximum is less than 0.003 second or about 0.001 second) the probable errors with the crusher-gage method will be greater than 5000 pounds per square inch.

The quicker the powder the greater is the excess of actual over indicated pressures and, for this reason, the error of the crusher gage is greater for small arms than for cannon.

5. NECESSITY OF PRELIMINARY PRECOMPRESSION

Though the crusher-gage method is very old, there remains up to the present time a problem of great importance—the necessity of precompression. It has been stated by many experimenters that copper cylinders should be precompressed at a certain pressure before using for test. Capt. Blunt,[5] F. W. Jones,[6] Marshall,[7] and others state that copper should be compressed beforehand with a static pressure only slightly less than that which it is to undergo in the actual test.

Col. W. H. Tschappat[8] states that when the pressure in the gun is high and quickly developed, it is at first very much greater than the resistance offered by the copper cylinder. The excess of pressure over resistance in this case accelerates the mass of the piston and develops considerable velocity in it. The energy of the piston due to this velocity is finally absorbed by further compression of the copper; but in the early stages of compresssion the mass of the piston prevents as great a compression as would be

---

[4] Report of Development of a Photoretardograph and Its Application to the Dynamic Measurement of Resistance to Compression Offered by the Copper Cylinders Used in Crusher Gages, by Lieut. B. W. Dunn, Ordnance Construction Notes, pp. 69–85; Jan. 13, 1896.

[5] Report of Capt. Blunt, Report of Chief of Ordnance, pp. 929–943; 1892.

[6] F. W. Jones, Lectures to Young Gunmakers, Arms and Explosives, p. 58, April, 1901, and p. 139, March, 1912.

[7] Marshall, Explosives, p. 363.

[8] Lieut. Col. W. H. Tschappat, Ordnance and Gunnery, pp. 101–103; 1917.

obtained if the pressure acted directly upon the copper cylinder instead of through the piston.

It is therefore desirable to reduce the energy of the piston as much as possible, and this may be done in two ways: By reducing its weight and by limiting its travel and accompanying velocity. As far back as 1883 Sarrau and Vieille [9] [10] showed that deformation of copper cylinders depends upon the weight (mass) of the piston through which the pressure is communicated. Usually the piston is made as light as possible.

To limit the travel all copper cylinders are precompressed by a load, generally about 3000 pounds per square inch less than that expected in the gun. According to many statements, initially compressed cylinders always record more uniform results than the uncompressed cylinders do.

Many investigators are of the opinion that the influence of many factors which have an important bearing on the results of pressure testing are minimized by the use of initially compressed cylinders, and they believe also that it is to their advantage to check each cylinder by an initial compression. On the other hand, there is rather good evidence that very uniform results may be obtained with uncompressed cylinders when they are made extremely uniform.

Thus, as was said above, the necessity of precompression up to the present time is rather an open question. In order to obtain some more data for the solution of this problem, experiments were started by the Bureau of Standards in connection with the standardization of the crusher-gage method for pressure testing of small arms, ammunition, and powder.[11] So far, the experiments have been confined to static tests; these are described in this paper. The experiments were carried out in 1919; they consisted of a series of compressions of the cylinders on a standard 10 000-pound Riehlé Brothers testing machine, and some microscopic examinations of their longitudinal and cross sections. The results are given in the tables and diagrams, so that few explanatory notes are required.

[9] Sarrau et Vieille, Etude sur l'Emploi des Manomètres pour la Mesure des Pressions Développées par le Substances Explosives.

[10] The Interior Ballistic, by Col. Pashkevitch, translated from Russian by Lieut. Tasker H. Bliss.

[11] The standardization of the crusher-gage method was started by Dr. P. D. Merica under the supervision of Dr. G. K. Burgess.

II. COMPRESSION TESTS

1. METHODS OF COMPRESSION

The rate of compression was always about 0.07 inch per minute. Duration of load after balance was obtained in most cases was about 2½ seconds, during which time the beam was not falling down.

Two methods of applying the load were used:

(1) There was single application of load. As soon as balance was obtained, the load was removed; or in some cases the load was removed after a certain period—5 or 25 seconds.

(2) After the balance was obtained, which was always followed by drop of the beam about 3 seconds after original balance, the balance of beam was maintained by reapplying the same load.

2. MEASUREMENT

The measurements were then made with a 1/10 000-inch micrometer. Measurements of length were taken with the cylinders placed in the micrometer centrally, each length being measured several times and only the minimum length recorded. Diameters were measured several times and the average recorded. After compression the cylinders have a barrel shape and in some cases two diameters of each cylinder were measured; that is, diameter of base; also diameter of cross section midway between the bases.

The diameter of the cross section midway between the bases is called "maximum" in the tables, and, as was stated, it is an average value of several measurements. The diameter of the base is called "minimum" and is also an average of several measurements. The minimum diameter, because of the difficulty of obtaining the exact measurement, is only an approximate value.

3. PLAN OF DESIGNATION

There are two lots of copper crusher cylinders both annealed at 1200° F at the same plant, but at different times. These two lots are here called Series No. 1 and Series No. 2.

There are also two other sets annealed at another factory at 1000° F and 1200° F, respectively, and called Series No. 3. The dimensions are given in inches, time in seconds, weight in pounds. Certain figures omitted were disregarded in drawing up the average as doubtful for various reasons. The following symbols will be used:

L = initial length of cylinders.

D = initial diameter of cylinders.

A = initial cross-sectional area.

L_1 = length of cylinders after the first compression.

L_2 = length of cylinders after the second compression, and so on.

21607°—21——2

D_1 = diameter of cylinders after the first compression.

D_2 = diameter of cylinders after the second compression, and so on.

$L-L_1$ = change in length of cylinders after first compression.

$L-L_2$ = change in length of cylinders after the second compression, and so on.

4. RESULTS OF COMPRESSION TESTS

(a) EXPERIMENTS ON REPEATED APPLICATION OF SAME AND OF SMALLER LOADS

TABLE 1.—Experiments on Repeated Application of Same and of Smaller Loads

L_1 = length of cylinders after applying pressure of 30 000 lbs./in.^{2} for about 30 seconds.
L_2 = length of cylinders after applying pressure of 40 000 lbs./in.^{2} for about 30 seconds.
L_3 = length of cylinders after applying pressure of (Note a) and (Note b) lbs./in.^{2} for about 30 seconds.
L_4 = length of cylinders after applying pressure of 38 000 lbs./in.^{2} for about 2½ seconds.
L_5 = length of cylinders after applying pressure of 36 000 lbs./in.^{2} for about 2½ seconds.
L_6 = length of cylinders after applying pressure of 34 000 lbs./in.^{2} for about 2½ seconds.
L_7 = length of cylinders after applying pressure of 30 000 lbs./in.^{2} for about 2½ seconds.
L_8 = length of cylinders after applying pressure of 25 000 lbs./in.^{2} for about 2½ seconds.

No.	L	D	A	Load equivalent to 30 000 lbs./in.^{2}	$L-L_1$	D_1 maximum	Load equivalent to 40 000 lbs./in.^{2}	$L-L_2$	D_2 maximum	Load equivalent to— (See a or b)	$L-L_3$	Load equivalent to 38 000 lbs./in.^{2}
	Inch	Inch	Inch^2	Lbs.	Inch	Inch	Lbs.	Inch	Inch	Lbs.	Inch	Lbs.
1	0.5004	0.2514	0.0495	1485	0.0494	0.2672	1980	0.0814	0.2780	[a] 1980	....	1881
2	.5009	.2516	.0497	1491	.0490	.2675	1988	.0786	.2778	[a] 1988	....	1888
3	.5003	.2516	.0497	1491	.0484	.2675	1988	.0786	.2768	[a] 1988	....	1888
4	.5006	.2517	.0497	1491	.0485	.2678	1988	.0802	.2781	[a] 1988	....	1888
5	.5004	.2514	.0495	1485	.0487	.2669	1980	.0786	.2772	[a] 1980	....	1881
6	.4996	.2516	.0497	1491	.0482	.2673	1988	.0799	.2784	[b] 1888	0.0816	1888
7	.5009	.2517	.0497	1491	.0482	.2677	1988	.0799	.2780	[b] 1888	.0810	1888
8	.5010	.2517	.0497	1491	.0501	.2673	1988	.0794	.2777	[b] 1888	.0823	1888
9	.5013	.2518	.0497	1491	.0480	.2672	1988	.0786	.2774	[b] 1888	.0808	1888
10	.5003	.2517	.0497	1491	.0492	.2673	1988	.0798	.2777	[b] 1888	.0820	1888
Average	....	....	....	....	.0488	....	....	.0795	....	....	.0815	....

No.	$L-L_4$	D_4 maximum	D_4 minimum	Load equivalent to 36 000 lbs./in.^{2}	$L-L_5$	Load equivalent to 34 000 lbs./in.^{2}	$L-L_6$	Load equivalent to 30 000 lbs./in.^{2}	D_7 maximum	D_7 minimum	$L-L_7$	Load equivalent to 25 000 lbs./in.^{2}	$L-L_8$
	Inch	Inch	Inch	Lbs.	Inch	Lbs.	Inch	Lbs.	Inch	Inch	Inch	Lbs.	Inch
1	....	0.2790	0.2669	1782	....	1683	....	1485	0.2795	0.2679	....	1237	......
2	....	.2790	.2669	1789	....	1690	....	1491	.2795	.2675	....	1243	......
3	....	.2780	.2660	1789	....	1690	....	1491	.2785	.2675	....	1243	......
4	....	.2800	.2645	1789	....	1690	....	1491	.2805	.2675	....	1243	......
5	....	.2790	.2660	1782	....	1683	....	1485	.2790	.2675	....	1237	......
6	0.0837	.2790	.2650	1789	0.0842	1690	0.0861	1491	.2796	.2675	0.0867	1243	0.0867
7	.0842	.2795	.2650	1789	.0851	1690	.0861	1491	.2788	.2675	.0865	1243	.0872
8	.0843	.2790	.2669	1789	.0850	1690	.0859	1491	.2798	.2675	.0863	1243	.0864
9	.0835	.2780	.2650	1789	.0862	1690	.0877	1491	.2800	.2675	.0880	1243	.0880
10	.0835	.2785	.2660	1789	.0848	1690	.0862	1491	.2795	.2675	.0866	1243	.0868
Av.	.0838	....	....	....	.0851	....	.0865	....	....	....	.0868	....	.0870

[a] Load in pounds equivalent to 40 000 lbs./in.^{2} [b] Load in pounds equivalent to 38 000 lbs./in.^{2}

Notes on Table 1.—Experiments were made upon copper crusher cylinders of Series I. The first and second compressions were made January 31, 1919. The third compression was made February 13, 1919. All three compressions were made under condition (2), stated above, keeping beam balanced for about 30 seconds after balance was obtained. The rest of the compressions

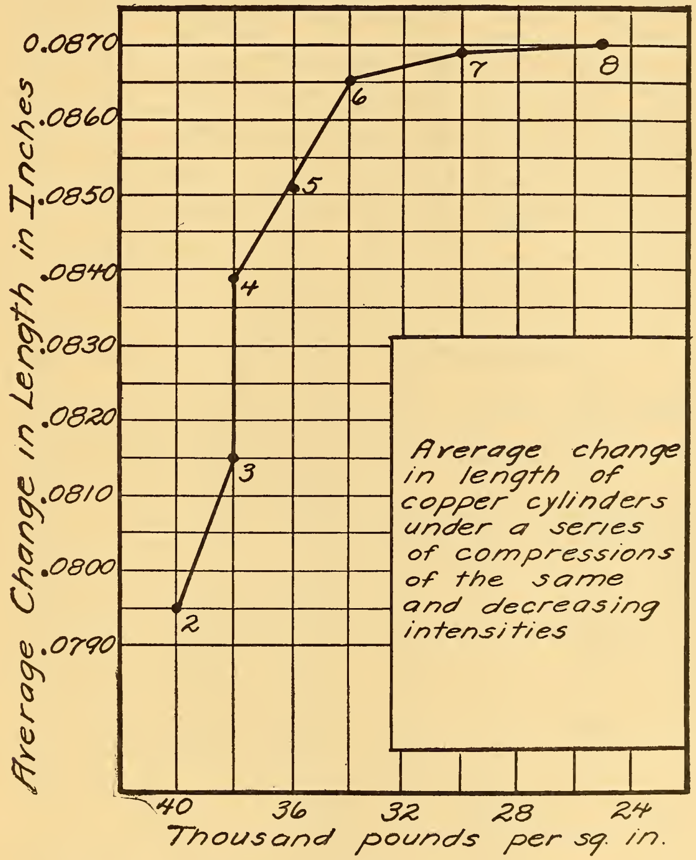

Fig. 3.—*Change of length of copper cylinders upon compression*

(compressions 4–8) were made May 17–19, 1919, under condition (1), with single application of load for about 2½ seconds.

As is shown in Fig. 3, the length of the copper cylinders decreases considerably under repeated application of the same and even smaller loads; this is in spite of the fact that the first three compressions were made keeping the beam in a balanced position for about 30 seconds.

TABLE 2.—Experiments on Repeated Application of Decreasing Loads

L_1=length of cylinders after applying pressure of 30 000 lbs./in.² for about 30 seconds.
L_2=length of cylinders after applying pressure of 28 000 lbs./in.² for about 2½ seconds.
L_3=length of cylinders after applying pressure of 25 000 lbs./in.² for about 2½ seconds.

No.	L	D	A	Load equivalent to 30 000 lbs./in.²	$L-L_1$	D_1 maximum	Load equivalent to 28 000 lbs./in.²	$L-L_2$	Load equivalent to 25 000 lbs./in.²	L_3	$L-L_3$
	Inch	Inch	Inch²	Pounds	Inch	Inch	Pounds	Inch	Pounds	Inch	Inch
1	0.5010	0.2517	0.0497	1491	0.0486	0.2674	1391	0.0491	1243	0.4515	0.0495
2	.5001	.2517	.0497	1491	.0496	.2675	1391	.0505	1243	.4496	.0505
3	.4999	.2515	.0496	1488	.0482	.2671	1388	.0494	1240	.4502	.0497
4	.5010	.2517	.0497	1491	.0475	.2668	1391	.0496	1243	.4500	.0510
5	.5006	.2515	.0496	1488	.0481	.2670	1388	.0507	1240	.4499	.0507
6	.5002	.2515	.0496	1488	.0482	.2670	1388	.0505	1240	.4487	.0515
7	.4998	.2518	.0497	1491	.0468	.2663	1391	.0483	1243	.4505	.0493
8	.5000	.2516	.0497	1491	.0468	.2668	1391	.0484	1243	.4505	.0495
9	.5005	.2515	.0496	1488	.0467	.2677	1388	.0484	1240	.4503	.0502
10	.5003	.2514	.0495	1485	.0482	.2665	1386	.0501	1237	.4493	.0510
Average					.0478			.0495			.0503

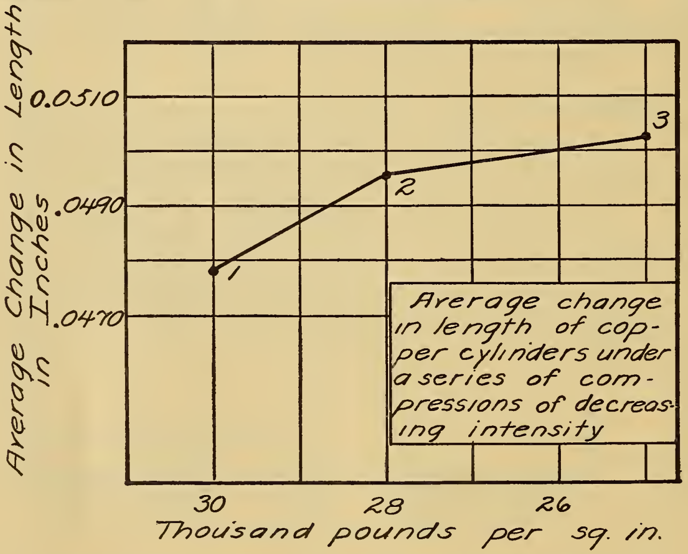

FIG. 4.—*Change of length of copper cylinders upon compression*

NOTES ON TABLE 2.—Experiments were made with copper cylinders of same stock as those of Table No. 1. The first compression was made February 1, 1919, with load of 30 000 pounds per square inch applied under condition (2), keeping the beam balanced for about 30 seconds.

The second and third compressions were made May 20, 1919, with single application of load 28 000 and 25 000 pounds per square inch for about 2½ seconds under condition (1). Fig. 4 indicates that repeated application of decreasing loads gradually decreases length of cylinders (within certain limits).

TABLE 3.—Experiments on Repeated Application of Same Load

No.	L	D	A	Load equivalent to 40 000 lbs./in.²	D_1 maximum	D_1 minimum	$L-L_1$	$L-L_2$	$L-L_3$
	Inch	Inch	Inch²	Pounds	Inch	Inch	Inch	Inch	Inch
1	0.4010	0.2265	0.04029	1612	0.2500	0.2350	0.0618	....	....
2	.4008	.2260	.04012	1604	.2485	.2350	.0586	0.0616	0.0638
3	.4005	.2256	.03997	1599	.2490	.2350	.0608	.0645	.0658
4	.4004	.2261	.04015	1606	.2468	.2350	.0547	....	....
5	.4005	.2262	.04018	1607	.2483	.2350	.0579	.0614	.0640
6	.4002	.2267	.04036	1614	.2498	.2350	.0602	.0630	.0646
7	.4002	.2267	.04036	1614	.2502	.2350	.0603	.0633	.0654
8	.4007	.2262	.04018	1607	.2493	.2350	.0593	.0630	.0657
9	.4004	.2266	.04033	1613	.2494	.2350	.0592	.0624	.0644
10	.4001	.2261	.04015	1606	.2486	.2350	.0587	.0618	.0635
Average	....	....	....	....	....	....	.0592	.0626	.0646

No.	$L-L_4$	D_4 maximum	D_4 minimum	$L-L_5$	D_6 maximum	D_6 minimum	$L-L_6$	$L-L_7$	$L-L_8$
	Inch	Inch	Inch	Inch	Inch	Inch	Inch	Inch	Inch
1	....	0.2525	0.2386	....	0.2530	0.2405	....	....	....
2	0.0673	.2514	.2386	0.0687	.2517	.2405	0.0697	0.0709	0.0735
3	.0682	.2514	.2386	.0696	.2522	.2405	.0714	.0736	.0753
4	....	.2498	.2386	....	.2505	.2405	....	....	....
5	.0659	.2505	.2386	.0670	.2510	.2405	.0682	.0694	.0703
6	.0670	.2519	.2386	.0702	.2532	.2405	.0708	.0719	.0726
7	.0666	.2520	.2386	.0682	.2534	.2405	.0698	.0721	.0740
8	.0685	.2516	.2386	.0700	.2526	.2405	.0709	.0727	.0746
9	.0675	.2519	.2386	.0693	.2534	.2405	.0717	.0734	.0748
10	.0665	.2508	.2386	.0675	.2518	.2405	.0693	.0710	.0732
Average	.0672	....	....	.0688	....	....	.0702	.0718	.0735

TABLE 4.—Experiments on Repeated Application of Same Load

No.	L	D	A	Load equivalent to 32 000 lbs./in.²	D_1 maximum	D_1 minimum	$L-L_1$
	Inch	Inch	Inch²	Pounds	Inch	Inch	Inch
1	0.4001	0.2260	0.04012	1284	0.2408	0.2295	0.0410
2	.3998	.2260	.04012	1284	.2408	.2295	.0389
3	.3999	.2264	.04026	1288	.2409	.2295	.0388
4	.4000	.2270	.04047	1295	.2425	.2295	.0409
5	.4002	.2264	.04026	1288	.2413	.2295	.0401
6	.3998	.2264	.04026	1288	.2410	.2295	.0391
7	.4005	.2262	.04018	1286	.2410	.2295	.0400
8	.4002	.2264	.04026	1288	.2414	.2295	.0402
9	.4000	.2264	.04026	1288	.2414	.2295	.0404
10	.3997	.2260	.04012	1284	.2415	.2295	.0403
Average	....	....	....	....	....	....	.0400

TABLE 4.—Experiments on Repeated Application of Same Load—Continued

No.	$L-L_2$	$L-L_3$	$L-L_4$	$L-L_5$	D_6 maximum	D_6 minimum	$L-L_6$
	Inch	Inch	Inch	Inch	Inch	Inch	Inch
1	0.0425	0.0450	0.0481	0.0492	0.2442	0.2345	0.0510
2	.0407	.0430	.0445	.0454	.2430	.2345	.0472
3	.0407	.0438	.0458	.0469	.2438	.2345	.0488
4	.0430	.0444	.0458	.0473	.2447	.2345	.0480
5	.0420	.0434	.0445	.0460	.2435	.2345	.0474
6	.0418	.0445	.0455	.0469	.2435	.2345	.0477
7	.0417	.0432	.0446	.0472	.2438	.2345	.0489
8	.0426	.0441	.0461	.0482	.2440	.2345	.0494
9	.0430	0456	.0468	.0482	.2430	.2345	.0497
10	.0423	.0450	.0469	.0480	.2442	.2345	.0498
Average	.0420	.0442	.0459	.0473			.0488

TABLE 5.—Experiments on Repeated Application of Same Load

No.	L	D	A	Load equivalent to 20 000 lbs./in.²	D_1 maximum	D_1 minimum	$L-L_1$
	Inch	Inch	Inch²	Pounds	Inch	Inch	Inch
1	0.4000	0.2256	0.03997	799	0.2315	0.2265	0.0165
2	.4001	.2257	.04001	800	.2319	.2265	.0161
3	.4000	.2267	.04036	807	.2332	.2270	.0172
4	.4000	.2257	.04001	800	.2328	.2260	.0185
5	.4002	.2263	.04022	804	.2332	.2265	0177
6	.4000	.2263	.04022	804	.2323	.2270	.0161
7	.3999	.2262	.04019	803	.2328	.2265	.0172
8	.4000	.2255	.03994	799	.2323	.2265	.0175
9	.4000	.2261	.04015	803	.2319	.2265	.0156
10	.4002	.2263	.04022	804	.2324	.2265	.0164
Average							.0169

No.	$L-L_2$	$L-L_3$	$L-L_4$	$L-L_5$	D_6 maximum	D_6 minimum	$L-L_6$
	Inch	Inch	Inch	Inch	Inch	Inch	Inch
1	0.0187	0.0196	0.0202	0.0207	0.2328	0.2264	0.0216
2	.0181	.0194	.0207	.0208	.2334	.2264	.0220
3	.0182	.0194	.0205	.0213	.2343	.2264	.0218
4	.0196						
5	.0199	.0213	.0221	.0233	.2352	.2264	.0246
6	.0173	.0182	.0191	.0197	.2336	.2264	.0209
7	.0191	.0204	.0212	.0228	.2346	.2264	.0235
8	.0195	.0207	.0219	.0223	.2338	.2264	.0236
9	.0164	.0184	.0191	.0200	2341	.2264	.0205
10	.0175	.0188	.0205	.0214	.2340	.2264	.0226
Average	.0184	.0196	.0206	.0214			.0223

NOTES ON TABLES 3, 4, AND 5.—These tables represent the results of experiments with cylinders of Series No. 2 by subjecting them to repeated compressions with single application of same load for about 2½ seconds.

The repeated loads were:

Table	Load
	Lbs./in.²
3	40 000
4	32 000
5	20 000

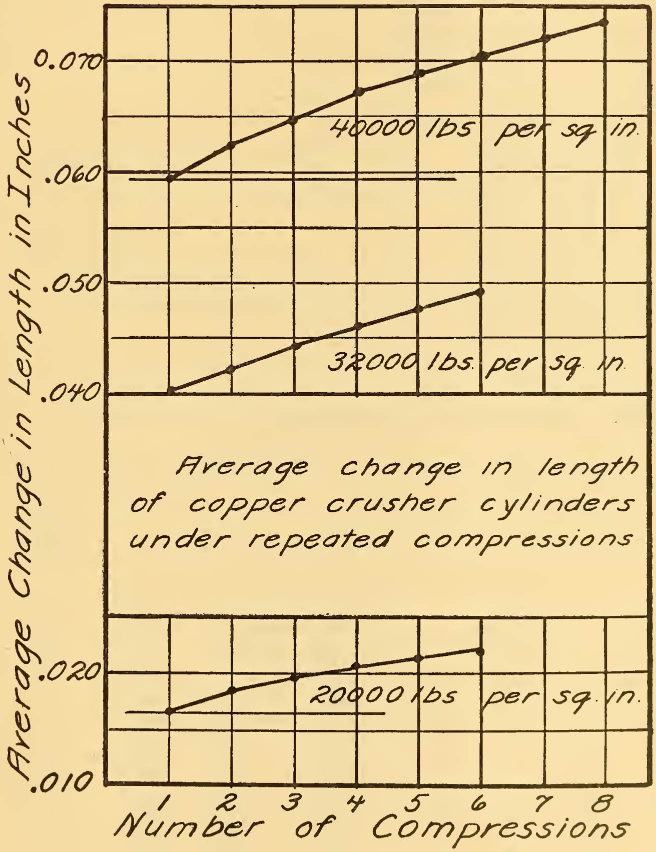

FIG. 5.—*Change of length of copper cylinders upon repeated compression*

All results are shown in Fig. 5.

The following conclusions may be drawn from these curves:

(1) The length of cylinders decreases considerably with the number of times the load is applied.

(2) This change also decreases slightly with number of application of load as the hardness of copper increases.

(3) The slope of the curve representing results of repeated compression with the load *P* is steeper than slope of curve representing results of repeated compression with the load *Q* if load *P* is greater than *Q*.

(b) EXPERIMENTS ON EFFECT OF DURATION OF COMPRESSION APPLIED UNDER CONDITION (1)

TABLE 6.—Experiments on Effect of Duration of Compression Applied Under Condition (1)

L_1=length of cylinders after applying pressure of 40 000 lbs./in.^{2} for about 2½ seconds.

No.	L	D	A	Load equivalent to 40 000 lbs./in.^{2}	$L-L_1$	No.	L	D	A	Load equivalent to 40 000 lbs./in.^{2}	$L-L_1$
	Inch	Inch	Inch^2	Lbs.	Inch		Inch	Inch	Inch^2	Lbs.	Inch
1	0.3999	0.2258	0.04004	1601	0.0587	10	0.3999	0.2264	0.04026	1610	0.0583
2	.4001	.2262	.04018	1607	.0588	11	.4002	.2260	.04012	1604	.0589
3	.4002	.2266	.04033	1613	.0587	12	.4001	.2257	.04001	1600	.0579
4	.4000	.2257	.04001	1600	.0570	13	.3999	.2259	.04008	1603	.0609
5	.3997	.2263	.04022	1609	....	14	.4000	.2264	.04026	1610	.0596
6	.3999	.2260	.04012	1604	.0579	15	.3999	.2257	.04001	1600	.0592
7	.3998	.2265	.04029	1612	.0591	Average	....	....	....	....	.0588
8	.4001	.2259	.04008	1603	.0589						
9	.3998	.2260	.04012	1604	.0601						

TABLE 7.—Experiments on the Effect of Duration of Compression Applied Under Condition (1)

L_1=length of cylinders after applying pressure of 40 000 lbs./in.^{2} for about 25 seconds.

No.	L	D	A	Load equivalant to 40 000 lbs./in.^{2}	$L-L_1$
	Inch	Inch	Inch^2	Pounds	Inch
1	0.3999	0.2256	0.03997	1598	0.0601
2	.4002	.2264	.04026	1610	....
3	.3999	.2262	.04018	1607	....
4	.4002	.2265	.04029	1612	.0594
5	.3999	.2262	.04018	1607	.0609
6	.3999	.2261	.04015	1606	.0600
7	.3998	.2256	.03997	1598	.0604
8	.4001	.2263	.04022	1609	.0603.
9	.3999	.2267	.04036	1614	.0600
10	.4000	.2262	.04018	1607	.0579
11	.4002	.2257	.04001	1600	.0580
12	.4002	.2257	.04001	1600	.0608
13	.4000	.2264	.04026	1610	.0578
14	.3998	.2262	.04018	1607	....
15	.3999	.2263	.04022	1609	.0602
16	.3998	.2261	.04015	1606	.0611
Average	....	....	....	....	.0598

TABLE 8.—Experiments on Effect of Duration of Compression Applied Under Condition (1)

L_1=length of cylinders after applying pressure of 40 000 lbs./in.² for about 5 seconds.

No.	L	D	A	Load equivalent to 40 000 lbs./in.²	$L-L_1$
	Inch	Inch	Inch²	Pounds	Inch
1	0.3999	0.2266	0.04033	1613	0.0579
2	.4009	.2263	.04022	1609	.0600
3	.4002	.2256	.03997	1598	.0597
4	.4001	.2265	.04029	1612	.0593
5	.4001	.2260	.04012	1604	.0585
6	.3998	.2258	.04004	1601	.0583
7	.4002	.2256	.03997	1598	.0592
8	.4002	.2265	.04029	1612	.0592
9	.3999	.2265	.04029	1612	.0595
10	.4000	.2256	.03997	1598	.0586
11	.4000	.2257	.04001	1600	.0593
12	.4000	.2267	.04036	1614	....
13	.4002	.2257	.04001	1600	.0609
14	.3998	.2260	.04012	1604	.0595
15	.3999	.2259	.04008	1603	.0609
Average	....	....	....	....	.0593

NOTES ON TABLES 6, 7, AND 8.—In this case experiments were made upon the cylinders of Series No. 2. Experiments consisted of compressions of 40 000 pounds per square inch applied under condition (1) for different periods, 2½, 5, and 25 seconds. Average changes in length are 0.0588, 0.0593, and 0.0598 inch, respectively. These experiments show slight increase of total set with increased time of application of load.

(*c*) EXPERIMENTS ON EFFECT OF TEMPERATURE OF ANNEALING

TABLE 9.—Experiments on Effect of Temperature of Annealing

[These copper cylinders were annealed at 1200° F (650° C).]

No.	L	D	A	Load equivalent to 30 000 lbs./in.²	D_1 maximum	$L-L_1$	Load equivalent to 35 000 lbs./in.²	$L-L_2$	Load equivalent to 40 000 lbs./in.²	$L-L_3$
	Inch	Inch	Inch²	Pounds	Inch	Inch	Pounds	Inch	Pounds	Inch
1	0.5002	0.2223	0.03881	1164	0.2355	0.0478	1358	0.0628	1552	0.0774
2	.5000	.2225	.03888	1166	.2356	.0478	1361	.0626	1555	.0780
3	.5000	.2226	.03892	1168	.2359	.0482	1362	.0624	1557	.0775
4	.5000	.2215	.03853	1156	.2342	.0473	1349	.0614	1541	.0764
5	.5003	.2221	.03874	1162	.2351	.0476	1356	.0624	1550	.0772
6	.5000	.2226	.03892	1168	.2357	.0487	1362	.0626	1557	.0783
7	.5002	.2231	.03909	1173	.2360	.0472	1368	.0610	1564	.0772
8	.5001	.2228	.03899	1170	.2361	.0480	1365	.0627	1560	.0774
9	.5001	.2225	.03888	1166	.2359	.0489	1361	.0627	1555	.0786
10	.4999	.2225	.03888	1166	.2355	.0477	1361	.0621	1555	.0772
11	.5002	.2218	.03864	1159	.2345	.0476	1352	.0616	1546	.0769
12	.5000	.2222	.03878	1163	.2353	.0486	1357	.0630	1551	.0783
Average	....	....	....	....	....	.0480	....	.0623	....	.0775

TABLE 10.—Experiments on Effect of Temperature of Annealing

[These cylinders were annealed at 1000° F (540° C)]

No.	L	D	A	Load equivalent to 30 000 lbs./in.²	$L-L_1$	D_1 maximum	Load equivalent to 35 000 lbs./in.²	$L-L_2$	Load equivalent to 40 000 lbs./in.²	$L-L_3$
	Inch	Inch	Inch²	Pounds	Inch	Inch	Pounds	Inch	Pounds	Inch
1	0.5003	0.2249	0.03973	1192	0.0456	0.2382	1391	0.0597	1589	0.0749
2	.5005	.2248	.03969	1191	.0465	.2378	1389	.0603	1588	.0756
3	.5010	.2255	.03994	1198	.0446	.2378	1398	.0589	1598	.0737
4	.5007	.2250	.03976	1193	.0464	.2381	1392	.0603	1590	.0756
5	.5007	.2257	.04001	1200	.0466	.2386	1400	.0609	1600	.0765
6	.5004	.2252	.03983	1195	.0458	.2382	1394	.0609	1593	.0748
7	.5004	.2250	.03976	1193	.0465	.3281	1392	.0606	1590	.0763
8	.5003	.2253	.03987	1196	.0450	.2379	1395	.0595	1595	.0733
9	.5004	.2253	.03987	1196	.0458	.2379	1395	.0601	1595	.0746
10	.5002	.2251	.03980	1194	.0461	.2378	1393	.0599	1592	.0748
11	.5005	.2254	.03990	1197	.0460	.2382	1397	.0604	1596	.0751
12	.5002	.2254	.03990	1197	.0454	.2379	1397	.0593	1596	.0744
Average					.0459			.0601		.0750

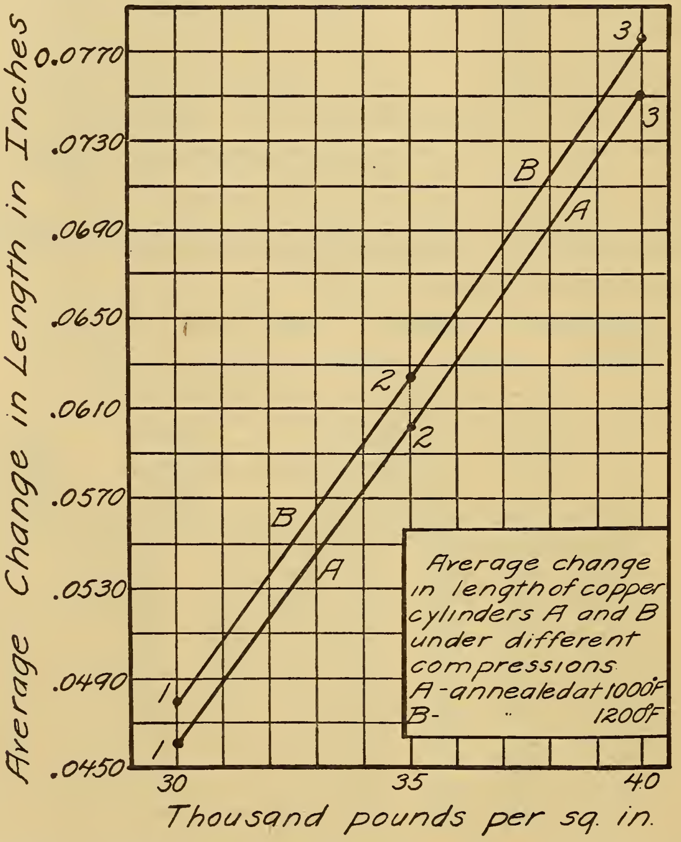

Fig. 6.—*Effect of annealing upon the change of length of copper cylinders upon compression*

NOTES ON TABLES 9 AND 10.—These tables represent experiments with copper cylinders of Series No. 3, annealed at 1000 and 1200° F (540 and 650° C). Different compressions (30 000, 35 000, and 40 000 pounds per square inch) were made keeping the load under condition (1) for about 2½ seconds. Fig. 6 indicates that copper cylinders annealed at 1200° F are softer than those annealed at 1000° F.

(*d*) EXPERIMENTS ON INFLUENCE OF INITIAL PRECOMPRESSION WHEN LOADS SUCCESSIVELY APPLIED DIFFER CONSIDERABLY FROM EACH OTHER

TABLE 11.—Experiments on Influence of Initial Precompression when Loads Successively Applied Differ Considerably from Each Other

L_1=length of cylinders after applying pressure of 20 000 lbs./in.² for about 2½ seconds.
L_2=length of cylinders after applying pressure of 32 000 lbs./in.² for about 2½ seconds.
L_3=length of cylinders after applying pressure of 40 000 lbs./in.² for about 2½ seconds.

No.	L	D	A	Load equivalent to 20 000 lbs./in.²	$L-L_1$	D_1 maximum	Load equivalent to 32 000 lbs./in.²	$L-L_2$	D_2 maximum	Load equivalent to 40 000 lbs./in.²	$L-L_3$	D_3 maximum
	Inch	Inch	Inch²	Lbs.	Inch	Inch	Lbs.	Inch	Inch	Lbs.	Inch	Inch
1	0.4000	0.2260	0.04012	802	0.0161	0.2322	1284	0.0395	0.2410	1605	0.0585	0.2481
2	.3998	.2264	.04026	805	.0168	.2331	1288	.0404	.2418	1610	.0596	.2494
3	.3998	.2257	.04001	800	.0175	.2327	1280	.0410	.2413	1600	.0607	.2494
4	.4000	.2259	.04008	802	.0180	.2323	1283	.0402	.2403	1603	.0595	.2487
5	.4000	.2253	.03987	797	.0156	.2318	1276	.0400	.2403	1595	......	......
6	.3998	.2261	.04015	803	.0154	.2322	1285	.0398	.2408	1606	.0594	.2490
7	.3998	.2260	.04012	802	.0158	.2317	1284	.0400	.2402	1605	.0601	.2486
8	.4000	.2260	.04012	802	.0150	.2317	1284	.0375	.2400	1605	.0560	.2476
9	.3999	.2263	.04022	804	.0160	.2322	1287	.0399	.2414	1609	.0586	.2488
10	.4001	.2263	.04022	804	.0164	.2327	1287	.0399	.2412	1609	.0589	.2490
11	.3998	.2265	.04029	806	.0175	.2333	1289	.0413	.2427	1612	.0603	.2498
12	.4000	.2265	.04029	806	.0167	.2326	1289	.0396	.2412	1612	.0588	.2488
13	.4000	.2258	.04004	801	.0171	.2322	1281	.0407	.2413	1602	.0607	.2494
14	.3999	.2263	.04022	804	.0176	.2331	1287	.0406	.2415	1609	.0598	.2493
15	.3998	.2268	.04040	808	.0158	.2332	1293	.0396	.2420	1616	.0590	.2498
Average	......	......	......	......	.0165	......	......	.0400	......	......	.0593	......

NOTES ON TABLE 11.—Here are represented experiments with copper cylinders of Series No. 2. Successive compressions (20 000, 32 000, and 40 000 pounds per square inch) were made on same cylinders, keeping the load under condition (1) for about 2½ seconds.

Comparing the average changes in length of cylinders with those of other tables after the first compression, we can conclude that in this case change in length depends only on value of load of the last compression, no matter whether previous compressions had been made or not.

After the first compression of 32 000 pounds per square inch, Tables 4 and 12 show an average $L-L_1$ of 0.0400 inch. After two compressions, the first of which was 20 000 pounds per square inch and the last 32 000 pounds per square inch, Table No. 11 shows an average $L-L_2$ of 0.0400 inch.

After first compression of 40 000 pounds per square inch:

Table No.	Results of first compression $L-L_1$
	Inch
6	0.0588
8	.0592
16	.0589
19	.0588

After three compressions, the first of which was 20 000 pounds per square inch, the second 32 000, and the third 40 000 pounds per square inch, Table 11 shows an average $L-L_3$ of 0.0593 inch. Comparing these figures—that is, 0.0400 with 0.0400 inch, and 0.0593 with 0.0588, 0.0592, 0.0589, and 0.0588 inch—we see that a very close concordance was obtained. It must be noted, however, that this statement may apply only when previous loads differ considerably from the last load, as was the case in these experiments. (The first load was 20 000, the second load 32 000, and the last load was 40 000 pounds per square inch.)

(e) EXPERIMENTS ON EFFECT OF INITIAL PRECOMPRESSION WHEN DIFFERENCES BETWEEN LOADS SUCCESSIVELY APPLIED ARE ONLY SLIGHT

TABLE 12.—Experiments on the Effect of Initial Precompression when the Differences Between the Loads Successively Applied are only Slight

L_1=length of cylinders after pressure of 32 000 lbs./in.² for about 2½ seconds.
L_2=length of cylinders after pressure of 36 000 lbs./in.² for about 2½ seconds.
L_3=length of cylinders after pressure of 38 000 lbs./in.² for about 2½ seconds.
L_4=length of cylinders after pressure of 40 000 lbs./in.² for about 2½ seconds.

No.	L	D	A	Load equivalent to 32 000 lbs./in.²	$L-L_1$	D_1 maximum	Load equivalent to 36 000 lbs./in.²
	Inch	Inch	Inch²	Pounds	Inch	Inch	Pounds
1	0.3998	0.2258	0.04004	1281			
2	.3999	.2262	.04018	1286	0.0403	0.2410	1446
3	.3999	.2257	.04001	1280	.0405	.2410	1440
4	.3999	.2261	.04015	1285	.0384	.2411	1445
5	.3997	.2258	.04004	1281	.0386	.2407	1441
6	.3997	.2267	.04036	1292	.0407	.2425	1453
7	.3999	.2267	.04036	1292	.0409	.2422	1453
8	.3999	.2263	.04022	1287	.0391	.2415	1448
9	.3999	.2265	.04029	1289	.0392	.2417	1450
10	.3999	.2267	.04036	1292	.0409	.2423	1453
11	.3998	.2267	.04036	1292	.0408	.2425	1453
12	.3997	.2260	.04012	1284	.0399	.2413	1444
13	.3995	.2259	.04008	1283	.0398	.2410	1443
14	.3996	.2263	.04022	1287	.0408	.2412	1448
15	.3997	.2268	.04040	1293			
Average					.0400		

TABLE 12.—Experiments on the Effect of Initial Precompression when the Differences Between the Loads Successively Applied are only Slight—Continued

No.	$L-L_2$	Load equivalent to 38 000 lbs./in.²	$L-L_3$	Load equivalent to 40 000 lbs./in.²	$L-L_4$	Load D_4 maximum
	Inch	Pounds	Inch	Pounds	Inch	Inch
1	....	....	....	....	....	....
2	0.0496	1527	0.0570	1607	0.0624	0.2486
3	.0502	1520	.0561	1600	.0624	.2495
4	.0496	1526	.0553	1606	.0612	.2493
5	.0495	1522	.0550	1602	.0607	.2491
6	.0502	1534	.0573	1614	.0627	.2496
7	.0497	1534	.0557	1614	.0618	.2498
8	.0499	1528	.0560	1609	.0616	.2494
9	.0505	1531	.0563	1612	.0624	.2494
10	.0506	1534	.0568	1614	.0629	.2500
11	.0509	1534	.0575	1614	.0638	.2508
12	.0495	1525	.0551	1605	.0618	.2488
13	.0497	1523	.0553	1603	.0609	.2489
14	.0504	1528	.0566	1609	.0620	.2494
15	....	....	....	....	....	....
Average	.0500	....	.0562	....	.0620	....

TABLE 13.—Experiments on Effect of Initial Precompression when Differences Between Loads Successively Applied are only Slight

L_1 = length of cylinders after applying pressure of 36 000 lbs./in.² for about 2½ seconds.
L_2 = length of cylinders after applying pressure of 38 000 lbs./in.² for about 2½ seconds.
L_3 = length of cylinders after applying pressure of 40 000 lbs./in.² for about 2½ seconds.

No.	L	D	A	Load equivalent to 36 000 lbs./in.²	$L-L_1$	D_1 maximum	Load equivalent to 38 000 lbs./in.²	$L-L_2$	Load equivalent to 40 000 lbs./in.²	$L-L_3$	D_3 maximum
	Inch	Inch	Inch²	Pounds	Inch	Inch	Pounds	Inch	Pounds	Inch	Inch
1	0.3995	0.2260	0.04012	1444	0.0488	0.2447	1525	0.0545	1605	0.0610	0.2489
2	.3995	.2260	.04012	1444	.0486	.2445	1525	.0550	1605	.0601	.2488
3	.3994	.2263	.04022	1448	.0483	.2448	1528	.0549	1609	.0607	.2490
4	.3997	.2268	.04040	1454	.0500	.2452	1535	.0559	1616	.0622	.2506
5	.3997	.2262	.04018	1446	.0488	.2448	1527	.0557	1607	.0615	.2492
6	.3998	.2266	.04033	1452	.0501	.2451	1533	.0562	1613	....	....
7	.3994	.2257	.04001	1440	.0483	.2442	1520	.0553	1600	.0609	.2489
8	.3994	.2267	.04036	1453	.0496	.2458	1534	.0561.	1614	.0619	.2501
9	.3998	.2254	.03990	1436	.2447	.2448	1516	.0555	1596	.0613	.2486
10	.3997	.2255	.03994	1438	.0500	.2452	1518	.0564	1598	....	....
11	.4000	.2265	.04029	1450	.0499	.2455	1531	.0565	1612	.0625	.2500
12	.3996	.2258	.04004	1441	.0480	.2445	1522	.0550	1602	.0604	.2486
13	.4000	.2257	.04001	1440	.0505	.2451	1520	.0563	1600	.0628	.2492
14	.3999	.2256	.03997	1439	.0485	.2440	1519	.0548	1599	.0606	.2483
15	.3998	.2258	.04004	1441	.0501	.2450	1522	.0563	1602	.0625	.2495
Average	....	....	....	....	.0493	....	....	.0556	....	.0614	....

TABLE 14.—Experiments on the Effect of Initial Precompression when the Differences Between the Loads Successively Applied are only Slight

L_1 = length of cylinders after applying pressure of 38 000 lbs. in.² for about 2½ seconds.
L_2 = length of cylinders after applying pressure of 40 000 lbs. in.² for about 2½ seconds.

No.	L	D	A	Load equivalent to 38 000 lbs. in.²	$L-L_1$	D_1 maximum	Load equivalent to 40 000 lbs. in.²	$L-L_2$	D_2 maximum
	Inch	Inch	Inch²	Lbs.	Inch	Inch	Lbs.	Inch	Inch
1	0.3998	0.2267	0.04036	1534	0.0550	0.3483	1614	0.0620	0.2503
2	.4000	.2260	.04012	1525	.0528	.3465	1605	....	....
3	.4001	.2262	.04018	1527	.0533	.3466	1607	.0597	.2487
4	.3999	.2255	.03994	1518	.0549	.3466	1598	.0616	.2490
5	.3999	.2256	.03997	1519	.0530	.3465	1599	.0595	.2489
6	.4000	.2262	.04018	1527	.0540	.3467	1607	.0609	.2494
7	.3998	.2257	.04001	1520	.0556	.3468	1600	.0621	.2492
8	.4001	.2262	.04018	1527	.0540	.3464	1607	.0604	.2489
9	.4001	.2259	.04008	1523	.0528	.3467	1603	.0599	.2489
10	.4002	.2264	.04026	1530	.0538	.3470	1610	.0598	.2496
11	.4000	.2257	.04001	1520	.0546	.3469	1600	.0608	.2486
12	.4000	.2264	.04026	1530	.0540	.3468	1610	.0607	.2496
13	.4001	.2256	.03997	1519	.0539	.3463	1599	.0597	.2486
14	.4002	.2260	.04012	1525	....	....	....	....	....
15	.4003	.2263	.04022	1528	.0549	.3470	1609	.0608	.2492
Average	....	....	....	....	.0540	....	....	.0606	....

TABLE 15.—Effect of Initial Precompression when Differences Between Loads Successively Applied are only Slight

Reference	32 000 lbs. in.²	36 000 lbs. in.²	38 000 lbs. in.²	40 000 lbs. in.²
See Tables Nos. 4, 11, and 12	$L-L_1=0.0400$	$L-L_2=0.0500$	$L-L_3=0.0562$	$L-L_4=0.0620$
See Table No. 13	....	$L-L_1=0.0493$	$L-L_2=0.0556$	$L-L_3=0.0614$
See Table No. 14	....	....	$L-L_1=0.0540$	$L-L_2=0.0606$
See Tables Nos. 3, 6, 11, 16, and 19	....	....	....	$L-L_1=0.0590$

NOTES ON TABLES 12, 13, 14, AND 15.—Experiments were made upon cylinders of the same stock; that is, cylinders of the Series No. 2.

Successive compressions of 32 000, 36 000, 38 000, and 40 000 pounds per square inch were made under condition (1), keeping the load on for about 2½ seconds.

Average changes in length under initial and successive compressions are shown in Table 15. Here are collected from Tables 3, 4, 6, 11, 12, 13, 14, 16, and 19 average changes of length (total sets). These data show the difference between the change in length of cylinders which were compressed at load P and of those previously compressed using a load Q slightly lower than load P and then compressed at load P.

It should be noted that in the case where several successive loads, differing by 2000 to 4000 pounds per square inch, had previously been applied the total change of length increases as the number of loads previously applied increases. All these results agree with experiments made with repeated compressions of same and smaller (within certain limits) loads applied on copper which is known to have practically no yield point.

(*f*) EXPERIMENTS ON EFFECT OF DURATION OF COMPRESSION APPLIED UNDER CONDITION (2) AND COMPARISON OF RESULTS OF DIFFERENT METHODS OF LOADING

TABLE 16.—Experiments on Effect of Duration of Compression Applied Under Condition (2)

L_1=length of cylinders after applying load of 40 000 lbs./in.^{2} for about 2½ seconds.

No.	L	D	A	Load equivalent to 40 000 lbs./in.^{2}	$L-L_1$	D_1 maximum
	Inch	Inch	Inch ^{2}	Pounds	Inch	Inch
1	0.4000	0.2261	0.04015	1606	0.0582	0.2485
2	.4004	.2259	.04008	1603	.0598	.2488
3	.4000	.2259	.04008	1603	.0587	.2487
4	....	....	....	....	....	....
5	.4003	.2259	.04008	1603	.0586	.2482
6	.3997	.2262	.04018	1607	.0579	.2484
7	.4005	.2265	.04029	1612	.0588	.2486
8	.4000	.2260	.04012	1604	.0588	.2488
9	.4000	.2266	.04033	1613	.0594	.2496
10	.4001	.2256	.03997	1599	.0601	.2489
Average	....	....	....	....	.0589	....

TABLE 17.—Experiments on Effect of Duration of Compression Applied Under Condition (2)

L_1=length of cylinders after applying pressure of 40 000 lbs./in.^{2}, holding beam balanced for about 5 seconds.

No.	L	D	A	Load equivalent to 40 000 lbs./in.^{2}	$L-L_1$	D_1 maximum
	Inch	Inch	Inch ^{2}	Pounds	Inch	Inch
1	0.3996	0.2263	0.04022	1609	....	0.2494
2	.3996	.2266	.04033	1613	.0589	.2497
3	.3995	.2263	.04022	1609	.0598	.2494
4	.3996	.2257	.04001	1600	.0611	.2494
5	.3995	.2268	.04040	1616	.0596	.2505
6	.3995	.2265	.04029	1612	.0594	.2495
7	.3996	.2259	.04008	1603	....	.2475
8	.3996	.2253	.03987	1595	.0596	.2490
9	.3996	.2263	.04022	1609	....	.2503
10	.3995	.2263	.04022	1609	.0590	.2493
11	.4002	.2258	.04004	1602	.0604	.2486
12	.4000	.2255	.03994	1598	.0594	.2487
Average	....	....	....	....	.0597	....

TABLE 18.—Experiments on Effect of Duration of Compression Applied Under Condition (2)

L_1= length of cylinders after applying pressure of 40 000 lbs./in.,[2] holding beam balanced for about 25 seconds.

	L	D	A	Load equivalent to 40 000 lbs./in.[2]	$L-L_1$	D_1 maximum
	Inch	Inch	Inch [2]	Pounds	Inch	Inch
1	0.4007	0.2262	0.04018	1607	0.0615	0.2495
2	.4003	.2261	.04015	1606	.0591	.2489
3	.4005	.2257	.04001	1600	.0590	.2485
4	.4003	.2262	.04018	1607	.0608	.2494
5	.4006	.2266	.04033	1613	.0609	.2505
6	.4006	.2257	.04001	1600	.0604	.2494
7	.4005	.2256	.03997	1599	.0613	.2488
8	.4005	.2258	.04004	1602	.0615	.2495
9	.4004	.2255	.03994	1598	.0611	.2486
10	.4008	.2263	.04022	1609	.0590	.2487
11	.4008	.2265	.04029	1612	.0611	.2495
12	.4008	.2264	.04026	1610	.0601	.2492
Average					.0605	

NOTES ON TABLES 16, 17, AND 18.—These tables represent the results of experiments made with cylinders of same series, No. 2, by subjecting them to compressions of 40 000 pounds per square inch applied under condition (2) for different periods—2½, 5, and 25 seconds—that is, holding beam balanced for these different periods.

In order to keep the beam balanced in this case only one additional application of same load (impulse) was needed after the beam had started to drop. Average changes in length are 0.0589, 0.0597, and 0.0605 inch, respectively.

It may be of interest to compare these results with those obtained in the experiments where the same load, 40 000 pounds per square inch, was held for different periods after the balance had been obtained and the beam allowed to drop, and also with those results obtained where the same load of 40 000 pounds per square inch was applied successively two times (for 2½ seconds each time), the second load being applied at some interval after the first load was entirely released.

1. In the case when load of 40 000 pounds per square inch was held for different periods after balance was obtained, the beam being allowed to drop (Tables 6, 7, and 8), the decrease in length of cylinders as compared with the length after compression for

2½ seconds (considering average change for 2½ seconds is equal to 0.0590 inch) is shown here:

Time of compression	Difference in decrease
Seconds	Inch
2½	0.0000
5	.0003
25	.0008

2. In case where same load of 40 000 pounds per square inch was held for different periods after balance was obtained, but holding beam balanced by means of one additional application of same load (Tables 16, 17, and 18), these differences were:

Time of compression	Difference in decrease
Seconds	Inch
2½	0.0000
5	.0007
25	.0015

3. In the case of one repeated application of the same load of 40 000 pounds per square inch (Table 4) the difference between the decrease in length after first and second applications for 2½ seconds each is 0.0626−0.0590 inch = 0.0036 inch. Hence it may be seen: (*a*) That the application of the same load for the same period (greater than 3 seconds), but made under condition (2)—that is, holding the beam balanced by means of one additional application (impulse) of the same load—causes about twice the decrease in length observed in the case when the beam is allowed to drop after the balance is obtained; (*b*) that where the load is applied twice (for 2½ seconds each time), the second load being applied at some intervals after the first load has been entirely released, the decrease in length is much greater than in the first two cases, even when the load is held there as long as 25 seconds.

(*g*) EXPERIMENTS ON AGING OF COPPER CYLINDERS OF SERIES No. 2, TABLES 19-25

The duration of the compression in these experiments was about 2½ seconds.

TABLE 19.—Compression Tests Relating to Experiments on Aging of Copper Cylinders

L_1=length of cylinders after applying pressure of 40 000 lbs./in.²

No.	L	D	A	Load equivalent to 40 000 lbs./in.²	$L-L_1$
	Inch	Inch	Inch²	Pounds	Inch
1	0.4001	0.2266	0.04033	1613	0.0599
2	.4002	.2259	.04008	1603	.0587
3	.4001	.2265	.04029	1612	.0596
4	.4001	.2258	.04004	1602	.0611
5	.4000	.2258	.04004	1602	.0592
6	.4001	.2259	.04008	1603	.0558
7	.4000	.2253	.03987	1595	.0618
8	.4000	.2255	.03994	1598	.0555
9	.4002	.2260	.04012	1605	.0592
10	.4003	.2265	.04029	1612	.0606
11	.4001	.2262	.04018	1607	.0578
12	.4002	.2264	.04026	1610	.0551
13	.4001	.2257	.04001	1600	.0608
14	.4004	.2258	.04004	1602	.0598
15	.4003	.2266	.04033	1613	.0579
Average					.0588

NOTES ON TABLE 19.—The table shows the mean total set of cylinders compressed at 40 000 pounds per square inch. The total set was 0.0599 inch.

TABLE 20.—Compression Tests Relating to Experiments on Aging of Copper Cylinders

L_1=length of cylinders after applying a pressure of 38 000 lbs./in.² for about 2½ seconds.
L_2=length of cylinders after applying a pressure of 40 000 lbs./in.² for about 2½ seconds, the pressure of 40 000 lbs./in.² being applied 1 hour after the pressure of 38 000 lbs.

No.	L	D	A	Load equivalent to 38 000 lbs./in.²	$L-L_1$	Load equivalent to 40 000 lbs./in.²	$L-L_2$
	Inch	Inch	Inch²	Pounds	Inch	Pounds	Inch
1	0.4002	0.2260	0.04012	1525	0.0530	1605	0.0612
2	.4002	.2261	.04015	1526	.0552	1606	.0622
3	.4004	.2257	.04001	1520	.0556	1600	.0619
4	.4001	.2265	.04029	1531	.0541	1612	.0616
5	.4001	.2260	.04012	1525	.0554	1605	.0616
6	.4005	.2262	.04018	1527	.0539	1607	.0594
7	.4001	.2258	.04004	1522	.0551	1602	.0608
8	.4003	.2263	.04022	1528	.0529	1609	.0595
9	.4005	.2263	.04022	1528	.0547	1609	.0612
10	.4001	.2259	.04008	1523	.0514	1603	
11	.4002	.2261	.04015	1526	.0517	1606	.0588
12	.4001	.2257	.04001	1520	.0545	1600	.0616
13	.4003	.2258	.04004	1522	.0513	1602	
14	.4003	.2258	.04004	1522	.0544	1602	.0606
15	.4005	.2257	.04001	1520	.0543	1600	.0607
Average					.0538		.0608

NOTES ON TABLE 20.—The cylinders were precompressed at 38 000 pounds per square inch, and one hour later they were compressed at 40 000 pounds per square inch. Total set was 0.0608 inch.

TABLE 21.—Compression Tests Relating to Experiments on Aging of Copper Cylinders

L_1=length of cylinders after applying a pressure of 38 000 lbs./in.^{2} for about 2½ seconds
L_2=length of cylinders after applying a pressure of 40 000 lbs./in.^{2} for about 2½ seconds, the pressure of 40 000 lbs. being applied after aging cylinders at 100° C during 28 days.

No.	*L*	*D*	*A*	Load equivalent to 38 000 lbs./in.^{2}	$L-L_1$	Load equivalent to 40 000 lbs./in.^{2}	$L-L_2$
	Inch	Inch	Inch^2	Pounds	Inch	Pounds	Inch
1	0.4005	0.2257	0.04001	1520	0.0551	1600	0.0632
2	.4003	.2258	.04004	1522	.0544	1602	.0626
3	.4006	.2257	.04001	1520	.0566	1600	.0627
4	.4004	.2257	.04001	1520	.0519	1600	.0596
5	.4005	.2263	.04022	1528	.0518	1609	.0582
6	.4001	.2263	.04022	1528	.0543	1609	.0618
7	.4002	.2264	.04026	1530	.0563	1610	.0641
8	.4003	.2258	.04004	1522	.0542	1602	.0614
9	.4003	.2264	.04026	1530	.0545	1610	.0627
10	.4003	.2265	.04029	1531	.0539	1612	.0618
11	.4005	.2255	.03994	1518	.0549	1598	.0628
12	.4000	.2262	.04018	1527	.0539	1607	.0619
13	.4004	.2270	.04047	1538	.0549	1619	.0623
14	.4000	.2258	.04004	1522	.0544	1602	.0615
15	.4002	.2260	.04012	1525	.0525	1605	.0615
Average					.0542		.0619

NOTES ON TABLE 21.—This table shows the results for copper cylinders, precompressed at 38 000 pounds per square inch, which had been held in an electric oven at 100° C for 28 days and then compressed at 40 000 pounds per square inch. The final total set in this case was 0.0619 inch.

TABLE 22.—Compression Tests Relating to Experiments on Aging of Copper Cylinders

L_1=length of cylinders after applying pressure of 38 000 lbs./in.² for about 2½ seconds.
L_2=length of cylinders after applying pressure of 40 000 lbs./in.² for about 2½ seconds, the pressure of 40 000 lbs./in.² being applied after aging cylinders at 0° and 100° C alternately during 28 days.

No.	L	D	A	Load equivalent to 38 000 lbs./in.²	$L-L_1$	Load equivalent to 40 000 lbs./in.²	$L-L_2$
	Inch	Inch	Inch ²	Pounds	Inch	Pounds	Inch
1	0.4004	0.2260	0.04012	1525	0.0558	1605	0.0636
2	.4001	.2259	.04008	1523	.0556	1603	.0630
3	.4001	.2260	.04012	1525	.0544	1605	.0624
4	.4004	.2263	.04022	1528	.0548	1609	.0613
5	.4001	.2261	.04015	1526	.0543	1606	.0624
6	.4002	.2260	.04012	1525	.0552	1605	.0637
7	.4000	.2259	.04008	1523	.0525	1603	.0593
8	.4001	.2268	.04040	1535	.0539	1616	.0626
9	.4003	.2258	.04004	1522	.0540	1602	.0624
10	.4002	.2267	.04036	1534	.0541	1614	.0618
11	.4002	.2259	.04008	1523	.0530	1603	.0614
12	.4000	.2267	.04036	1534	.0538	1614	.0609
13	.4005	.2254	.03990	1516	.0546	1596	.0622
14	.4000	.2257	.04001	1520	.0538	1600	.0615
15	.4005	.2261	.04015	1526	.0505	1606	.0575
Average					.0540		.0617

NOTES ON TABLE 22.—This table indicates that the final total set of 0.0617 inch was obtained on cylinders precompressed at 38 000 pounds per square inch and aged at 0 and 100° C, alternately, during 28 days and then compressed at 40 000 pounds per square inch.

TABLE 23.—Compression Tests Relating to the Experiments on Aging of Copper Cylinders

L_1=length of cylinders after applying pressure of 38 000 lbs./in.² for about 2½ seconds.
L_2=length of cylinders after applying pressure of 40 000 lbs./in.² for about 2½ seconds, the pressure of 40 000 lbs./in.² being applied after aging cylinders at room temperature for 30 days.

No.	L	D	A	Load equivalent to 38 000 lbs./in.²	$L-L_1$	Load equivalent to 40 000 lbs./in.²	$L-L_2$
	Inch	Inch	Inch ²	Pounds	Inch	Pounds	Inch
1	0.4008	0.2258	0.04004	1522	0.0506	1602	0.0537
2	.4008	.2257	.04001	1520	.0561	1600	.0636
3	.4005	.2257	.04001	1520	.0558	1600	.0641
4	.4007	.2260	.04012	1525	.0560	1605	.0617
5	.4007	.2262	.04018	1527	.0550	1607	.0612
6	.4008	.2259	.04008	1523	.0550	1603	.0628
7	.4008	.2260	.04012	1525	.0537	1605	.0613
8	.4005	.2259	.04008	1523	.0527	1603	.0602
9	.4010	.2260	.04012	1525	.0552	1605	.0616
10	.4008	.2259	.04008	1523	.0555	1603	.0624
11	.4011	.2262	.04018	1527	.0553	1607	.0621
12	.4006	.2267	.04036	1534	.0547	1614	.0618
Average					.0546		.0614

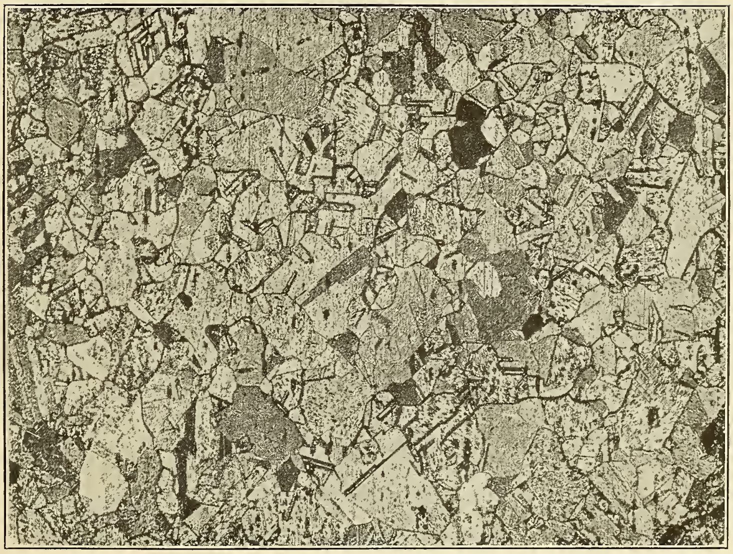

FIG. 7.—*Longitudinal section of copper cylinder annealed at 650° C.* × 100

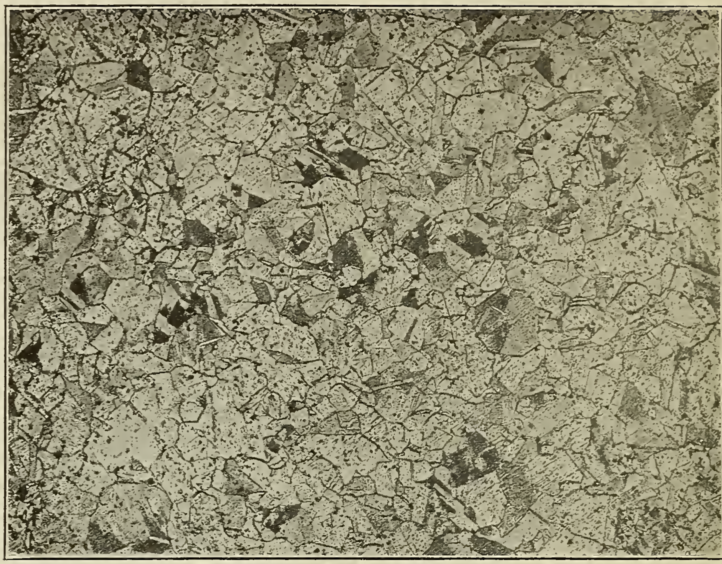

Fig. 8.—*Cross section of copper cylinder annealed at 650° C.* × *100*

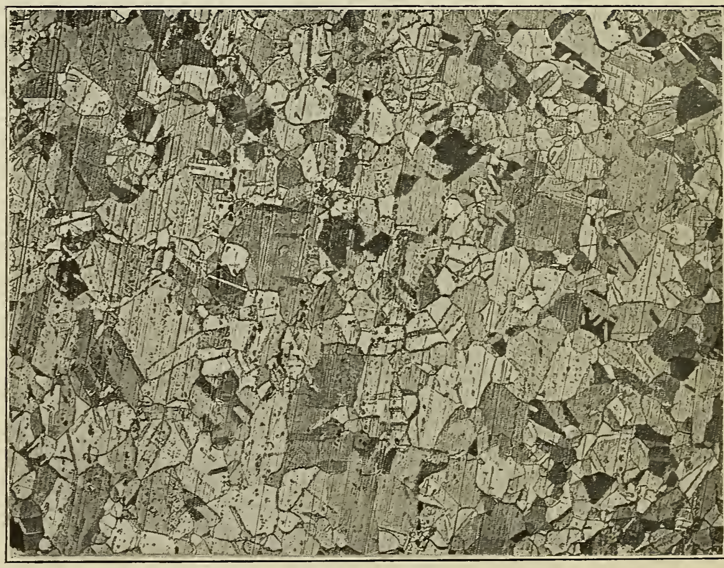

Fig. 9.—*Longitudinal section of copper cylinder annealed at 650° C.* × *100*

TABLE 24.—Compression Tests Relating to the Experiments on Aging of Copper Cylinders

L_1=length of cylinders after applying pressure of 38 000 lbs./in.² for about 2½ seconds.
L_2=length of cylinders after applying pressure of 40 000 lbs./in.² for about 2½ seconds, the pressure of 40 000 lbs./in.² being applied after aging cylinders at room temperature for 27 days.

No.	L	C	A	Load equivalent to 38 000 lbs./in.²	$L-L_1$	Load equivalent to 40 000 lbs./in.²	$L-L_2$
	Inch	Inch	Inch²	Pounds	Inch	Pounds	Inch
1	0.4000	0.2268	0.04040	1535	0.0547	1616	0.0630
2	.4001	.2260	.04012	1525	....	....	....
3	.3999	.2260	.04012	1525	.0525	1605	.0592
4	.3996	.2258	.04004	1522	.0550	1602	.0621
5	.3996	.2265	.04029	1531	.0529	1612	.0609
6	.4001	.2259	.04008	1523	.0524	1603	.0588
7	.4001	.2257	.04001	1520	.0551	1600	.0626
8	.4001	.2256	.03997	1519	.0544	1599	.0618
9	.3996	.2258	.04004	1522	.0561	1602	.0618
10	.4002	.2260	.04012	1525	.0547	1605	.0621
11	.3999	.2255	.03994	1518	.0541	1598	.0621
12	.3998	.2261	.04015	1526	.0548	1606	.0628
Average	....	....	....	....	.0542	....	.0616

NOTE ON TABLES 23 AND 24.—Cylinders precompressed at 38 000 pounds per square inch were aged at room temperature for 30 days and then compressed at 40 000 pounds per square inch. The mean total sets were 0.0614 and 0.0616 inch, respectively.

Intercomparing all results stated above (Table 25) it may be concluded that aging at temperatures of 0–100° C makes the compressed copper softer. It should be noted, however, that in the author's opinion the data in regard to aging is not sufficient; such an important problem needs very careful additional experiments in static as well as impact and firing tests after different periods of aging. The above results also are contradictory to those of H. W. R. Mason,[12] who found from his impact experiments that in copper crushers spontaneous annealing does not take place.

[12] H. W. R. Mason, Resistance of Copper Crushers during Compression, Arms and Explosives; July 1, 1918.

TABLE 25.—Table Showing Average Results on Effect of Aging on Reduction in Length of Compressed Copper Cylinders

Reference to cylinders	Precompression at 38 000 lbs./in.²		Compression at 40 000 lbs./in.²	
	Date of precompression	Average total set of cylinders per inch	Date of compression	Average total set of cylinders per inch
		Inch		Inch
Table 14	June 26, 1919	0.0540	One hour later of same day, June 26, 1919.	0.0606
Table 20	Aug. 29, 1919	.0538	One hour later of same day, Aug. 29, 1919.	.0608
Table 21	July 30, 1919	.0542	Aug. 27, 1919, after aging at 100° C from July 30 to Aug. 27.	.0619
Table 22	do	.0540	Aug. 27, 1919, after aging at 0° C and 100° C alternately from July 30 to Aug. 27.	.0617
Table 23	do	.0546	Aug. 29, 1919, after aging at room temperature from July 30 to Aug. 29.	.0614
Table 24	July 31, 1919	.0542	Aug. 27, 1919, after aging at room temperature from July 31 to Aug. 27.	.0616

III. MICROSCOPIC EXAMINATION

Longitudinal and cross sections of copper cylinders were examined microscopically (Figs. 7–15). In all cases the cylinders were etched with NH_4OH and H_2O_2.

In order to show distortion of grains under pressure, some micrographs were taken of the same spots before and after compression—that is, the cylinder was etched, the micrograph was taken, and the spot marked. Then the cylinder was compressed at 30 000 pounds per square inch, and a micrograph of the marked spot was taken again. This is shown in Figs. 12–15, where (Figs. 13 and 15) many slip bands may be seen.

IV. SUMMARY

Several conclusions may be drawn from these experiments, which only confirm the already known phenomena, as well as those expected from the known properties of copper:

1. The length of copper crusher cylinders decreases considerably under repeated compressions of the same load. The relation between this decrease in length and number of times load was applied is nearly proportional within certain limits.

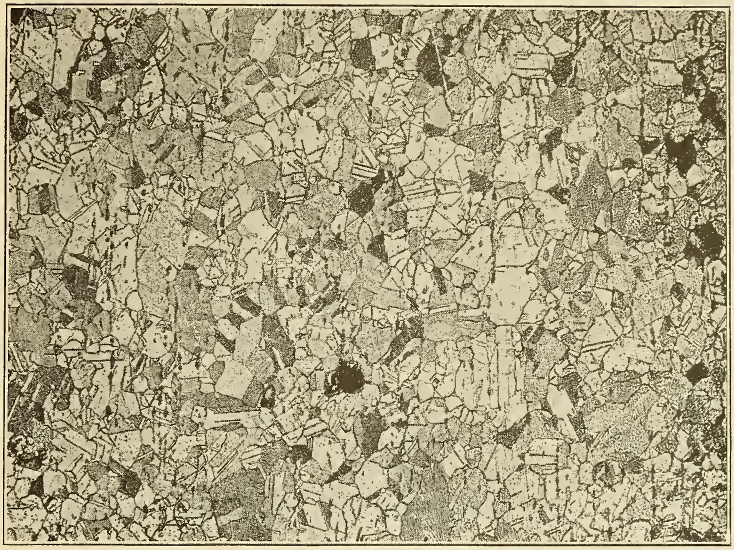

FIG. 10.—*Longitudinal section of copper cylinder annealed at 540° C. × 100*

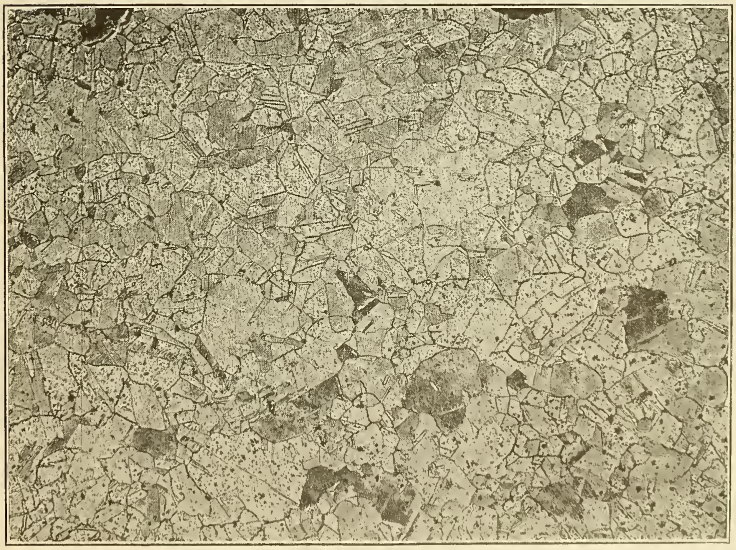

FIG. 11.—*Cross section of copper cylinder annealed at 540° C. × 100*

FIG. 12.—*Longitudinal section of copper cylinder annealed at 650° C. Micrograph represents the spot located midway bases and near to the axis of cylinder.* × 200

FIG. 13.—*Same cylinder and same spot as Fig. 12, but after compression at 30 000 lbs. per square inch.* × 200

Fig. 14.—*Longitudinal section of copper cylinder annealed at 650° C. Spot is located near one of the bases of the cylinder and very near its periphery.* × 200

Fig. 15.—*Same cylinder and same spot as in Fig. 14, but after compression at 30 000 lbs. per square inch.* × 200

2. The change in length with repeated constant loads is greater with the greater load.

3. Repeated application of successive decreasing loads causes a gradual decrease in length within certain limits.

4. The length changes but slightly with longer application of load when the load is applied in such a manner as to occasion the maximum stress only for an instant.

5. Application of the same load for the same period (greater than about 3 seconds), but holding the beam balanced by means of one additional application (impulse) of the same load after the beam had started to drop, causes about twice the decrease in length observed in the previous case, when the beam was allowed to drop after balance is obtained.

6. Double application of the same load for 2½ seconds each time, the second load being applied at some interval after the first load has been released, causes a decrease in length much greater than in the previous two cases. This holds true even when the pressure is applied for as long as 25 seconds in the case of paragraphs 4 and 5.

7. In case the last load is considerably greater than any previous loads, the change in length caused by the last load is practically independent of the previous loads—that is, it is the same as would be obtained by compressing a previously uncompressed cylinder.

8. When two successive loads of considerable amount (approximately 40 000 pounds per square inch) differing from one another by about 2 000 pounds per square inch, are applied, the second being greater than the first, the change in length due to the last load is considerably greater than that obtained where the pressure is applied on previously uncompressed cylinders, and this difference increases as the difference between the two loads successively applied decreases.

9. When several successive loads of considerable amount are applied, differing by about 2000 pounds per square inch, each greater than the preceding load, the total change in length of the cylinders due to the last compression increases with the number of loads previously applied.

10. Copper cylinders annealed at 1200° F 650° C are softer than those annealed at 1000° F 540° C.

11. It is probable that aging at temperatures within 0–100° C softens the compressed copper somewhat.

12. Concerning the use of precompressed or uncompressed copper cylinders the conclusion from these experiments may be drawn for cases when the checking of every copper cylinder by precompression is necessary, a precompression of the cylinders at a pressure of at least 8000 pounds per square inch below the expected maximum pressure can be employed without impairing the ability of the precompressed cylinders to register the maximum pressure in equally reliable manner as an uncompressed cylinder would.

WASHINGTON, October 15, 1920.